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Advanced laser transmission welding strategies for fibre reinforced thermoplastics

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Abstract

Laser transmission welding can be used to join endless fibre reinforced thermoplastics. The welding temperature is affected by the heat conduction along carbon fibres and depends on the local orientation of the fibres in the weld seam and the laser welding technique itself. In these investigations the heat development during the welding with quasi-static temperature fields, which is a combination of two laser welding techniques, is evaluated and compared to welding with a homogenized intensity distribution. In order to optimize the temperature distribution over the weld seam width for both linear and curved weld seams, different scanning structures have been adapted. The experiments were conducted with a diode laser emitting at a wavelength of 940 nm and the process was monitored by an infrared camera. The used thermoplastics consist of laminates based on unidirectional carbon fibre reinforced polyphenylenesulfide. With the developed scanning structures, a near-homogeneous temperature distribution was generated over the width of the weld seam for curved weld seams, which is not possible by welding with a homogenized laser radiation intensity distribution.

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Keywords: laser transmission welding; CFRP; thermoplastic; process monitoring; quasi-static temperature fields.

1. Introduction and Motivation

Today, fibre reinforced thermoplastic parts are used in applications in the automotive and the aerospace sector. For some applications, these parts are joined to complex structures along with other thermoplastic components.

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Therefore, flexible and reliable joining techniques are needed. Many different joining techniques exist for thermoplastic materials, such as hot plate, ultrasonic and vibration welding [1]. Another welding technique for these materials is laser transmission welding. During laser transmission welding, the laser radiation passes the natural finish, transparent part due to its transparency in the near infrared (NIR) spectral range. Parts of the radiation are absorbed by the matrix material and affected by reinforcements like glass fibres, which scatter the laser radiation [2, 3]. Thermoplastic material containing carbon fibres (CFRP) or the additive carbon black absorbs the NIR radiation and generates heat. Due to heat conduction between both joining members, the transparent part also melts. To support constant heat conduction between both parts, they have to be clamped with a constant pressure over the weld seam [4, 5]. Furthermore, carbon fibres in the absorbing member have an effect on the weld seam development. Carbon fibres have a high thermal conductivity compared to the matrix material. Consequently, the heat is conducted along the carbon fibres and the weld seam geometry is affected by the local orientation of these fibres relative to the weld seam (Fig.1b) [6].

Laser transmission welding can be divided into contour, quasi-simultaneous, simultaneous and mask welding. At the contour welding the laser beam passes the weld seam once. This welding technique can be used to generate long and three-dimensional weld seams [7]. During quasi-simultaneous welding, the laser beam is guided over the weld seam multiple times with a high speed by a scanner optic, generating heat in the weld seam slowly. During this welding process, the whole weld seam melts, which leads to a higher gap bridge capability [8, 9]. This welding technique is limited by the working field of scanner optics. The weld seam width is mainly affected by the focal diameter of the laser beam. For generating wider weld seams, the laser beam can be expanded and homogenized by a special optic or oscillated by a scanner optic, with the joining members moving relative to the scanner optic. The last welding method is a combination of contour and quasi-simultaneous welding and provides the possibility to generate quasi-static temperature fields [10]. Especially for processing wide weld seams with small radii, conventional welding techniques have to be adapted to generate a quasi-static temperature distribution over the width of the weld seam. Therefore, new scanning structures have been developed to optimize the temperature distribution over the weld seam width for bead on plate welding of unidirectional CFRP.

2. Experimental Set-up

The experiments were conducted with b = 1.2 mm thick unidirectional CFRP containing a fabric core and consisting of a polyphenylene sulfide (PPS) (Fig. 1a). The matrix material PPS has a glass transition temperature of T = 90°C and a melting temperature of T = 280°C. This material was used for bead on plate welding, which is used to investigate the heat development and conduction in the absorbing member while neglecting the effect of the transparent member on the welding process.

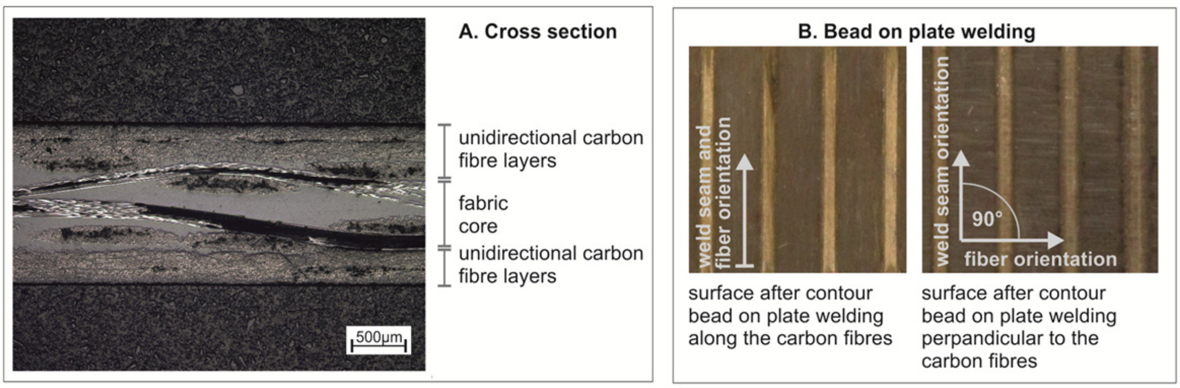

Fig. 1. (a) build-up of the unidirectional CFRP of the conducted investigations; (b) bead on plate weld on unidirectional CFRP surface.

The experiments were performed with a diode laser emitting at a wavelength of $\lambda = 940$ nm with a maximum laser power of $P = 300$ W. For these investigations two different optics were used: a welding head with a homogenized focal point of the dimension $d^2 = 5$ mm x 5mm, and a scanning optic generating a focal diameter of

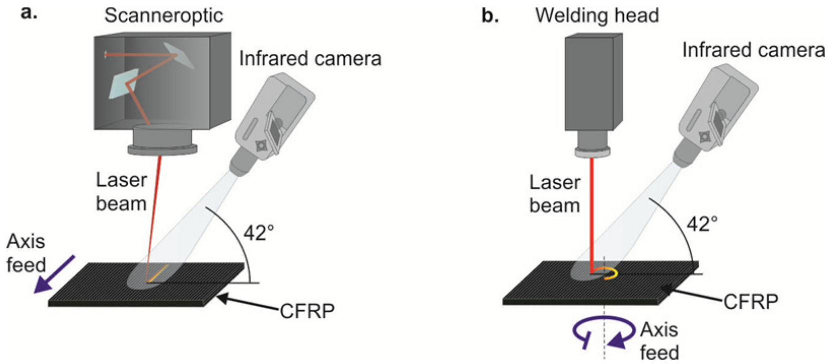

Fig. 2. (a) Example set-up for generating quasi-static temperature fields; (b) Example set-up for generation curved bead on plate weld seams with a welding head.

$d = 2$ mm (Fig. 2). The laser beam was guided by the scanning optic with a speed of $v = 500$ mm/s over the CFRP for the generation of different scanning structures. The laser power was adapted during the investigations to avoid degeneration of the material and the generation of smoke, which would affect the accuracy of the temperature measurement by the infrared camera. The CFRP was always moved relative to the welding area with a speed of $v_{Axis} = 10$ mm/s on a linear axis as well as a rotating axis. The inner radius of the curved bead on plate weld was $r = 2$ mm. The process temperature was monitored by an infrared camera. The infrared camera detects in the spectral range of $\lambda = 3.7 – 4.8$ µm with a maximum full frame rate of $f = 100$ Hz.

3. Results and Discussion

3.1 Laser contour welding with homogenized laser radiation intensity

As a first step the welding head with a homogenized weld spot was used to generate bead on plate welds on CFRP. The fibre orientation relative to the weld seam was 0° (CFRP UD 0) as well as 90° (CFRP UD 90). The process temperature was monitored by an infrared camera, which detects infrared radiation and forms a 2D pseudocolor image representing the temperature values. In this thermographic image a straight measuring line was placed in the area of the highest temperatures in the weld seam perpendicular to the axis feed. The maximum temperature for each pixel on this straight line was determined for the duration of each welding experiment. Based on these values a corresponding envelope was created representing the maximum temperatures occurred during the welding process.

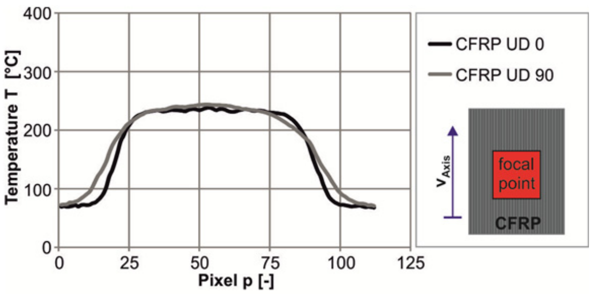

Fig. 3. Envelopes of the maximum temperatures for bead on plate welding on unidirectional CFRP with different fibre orientations.

The effect of the carbon fibre orientation on the maximum temperature distribution over the bead on plate weld width using a welding head is depicted in Fig. 3. On the CFRP UD 0, the temperature rises faster until it reaches its maximum value compared to the welding temperature on CFRP UD 90. These results indicate the heat conduction out of the weld seam on the CFRP UD 90 is higher than on the CFRP UD 0. Also, only with the CFRP UD 0 a nearly-constant maximum temperature distribution could be detected over the width of the weld seam. The envelope progression for CFRP UD 90 does not have a plateau with constant maximum temperatures.
The envelope for a curved weld seam shows an increase of the temperature toward the inner radius of the weld seam (Fig.4). This indicates an inhomogeneous temperature distribution while welding small radii with proportionally large laser spot diameter. An inhomogeneous temperature distribution could lead to a nonuniform weld seam development and a consequential decrease of the weld seam strength. In summary, with this focal point shape and intensity distribution a homogenized temperature distribution is generated for linear weld seams, whereas for curved weld seams a non-uniform temperature distribution over the width of the weld seam is induced.

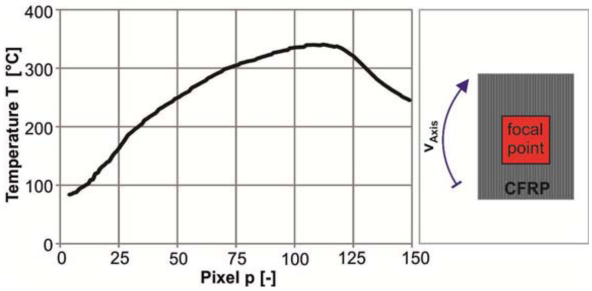

Fig. 4. Envelope of the maximum temperatures for curved bead on plate welding with a homogenized welding spot.

3.2 Laser welding with quasi-static temperature fields

To improve the homogeneity of the temperature distribution over the weld seam width, scanning structures were developed to generate quasi-static temperature fields for straight and curved weld seams. The scanning structures consist of four parallel lines orientated parallel or perpendicular to the axis feed. The scanning order of each set of scan lines in the welding process is given in the pictogram (Fig. 5). The envelope of the maximum temperatures of the scanning structure with lines perpendicular to the axis feed (A) shows a high temperature in the middle of the weld seam, which decreases towards the edges of the weld seam width. For the scanning structure consisting of lines parallel to the axis feed (B), the temperature rises over each scanning line and decreases between them. This scanning structures leads to four peaks with similar temperatures over the width of the weld seam.

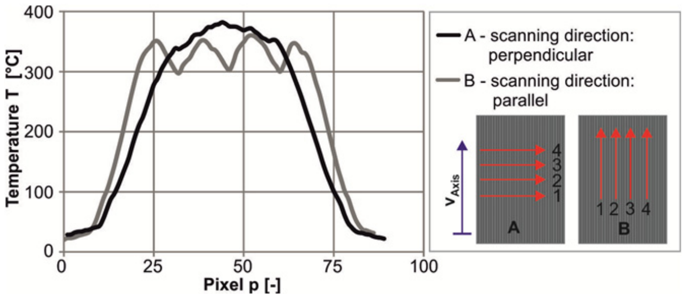

Fig. 5. Maximum temperature distribution on PSS UD 0 over the weld seam width for different scanning structures.

Additionally, the influence of the carbon fibre orientation relative to the weld seam orientation was investigated and is depicted in Fig. 6. For the scanning structure with lines parallel to the axis feed, the envelope of the maximum temperatures has higher values for the welding process on CFRP UD 0 than on CFRP UD 90. During the welding process parallel to the carbon fibres, the heat is mainly conducted ahead of and behind the scanning area, so the heat stays within the area of the weld seam. During the welding process on CFRP UD 90, the generated heat by the laser beam conducts along the carbon fibres outward from the weld seam. This leads to lower temperatures in the middle of one scanning line (i), but also to higher temperatures on the edge of the weld seam (ii). Furthermore, for the welding process on CFRP UD 90 the temperature difference between the temperature in the middle of each scanning line and the lower temperature between the scanning lines is not as high as for the envelope of the CFRP UD 0. This indicates a low thermal conductivity perpendicular to the carbon fibres and a more homogeneous heat distribution for the welding on CFRP UD 90. Additionally, the heat conduction, which leads in this case to a heat loss in the weld seam, is indicated by higher temperatures on the edge of the weld seam.

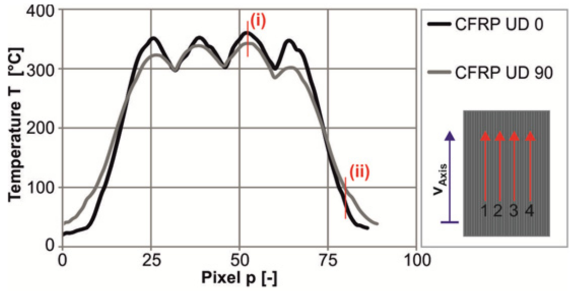

Fig. 6. Envelope of the temperatures on CFRP UD 0 and CFRP UD 90.

For the investigation on curved weld seams, the length of the scanning lines were adapted to enhance the temperature distribution over the width of the weld seam as shown in Figure 7. The characteristic temperature distribution for the scanning structure consisting of lines perpendicular to the centre of the axis was detected for conventional (C) and adapted scanning structures (D). The maximum temperature values of the envelopes increase toward to the inner radius of the weld seam, so the same tendency occurs as for the welding process conducted with the welding head. The difference between the maximum temperature on the outer scanning lines is about $\Delta T_n = 99°K$ for the conventional scanning structure. After the adaption of the scanning structure line length this temperature difference is reduced to $\Delta T_a = 37°K$, which is a reduction in temperature difference of about $\Delta T_{\%} = 63\%$.

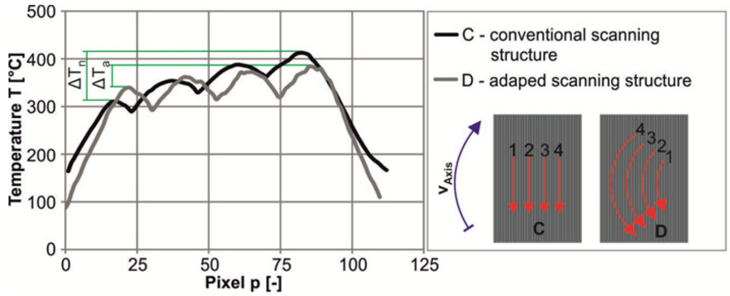

Fig. 7. Maximum temperature envelope for conventional and adapted scanning structures for curved welding processes.

To improve the temperature distribution over the weld seam width the scanning structure was rotated about 90° based on the results for the linear weld seams. The envelope for the scanning structure consisting of lines perpendicular to the axis feed on curved weld seams is depicted in Figure 8. For the conventional scanning structure (E) the temperature rises toward the inner radius of the weld seam. With the adapted scanning structure (F), more laser energy is applied to the outer radius and thus a near-homogeneous temperature distribution over the width of the weld seam is realized. So, a scanning structure was realized to generate a near-homogeneous temperature distribution for welding small radii.

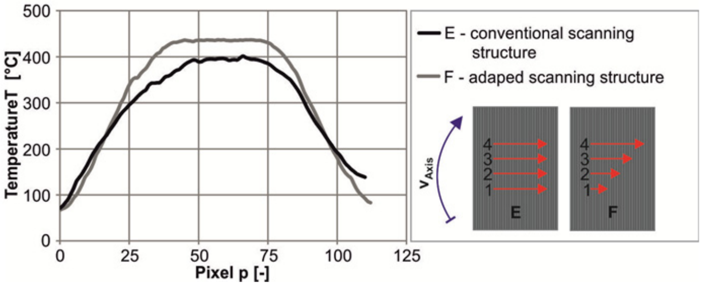

Fig. 8. Envelopes of the maximum temperatures generated with scanning lines perpendicular to the axis feed.

4. Conclusion

In these investigations the temperature distribution over the weld seam width for linear and curved bead on plate welds on laminates based on unidirectional carbon fibre reinforced polyphenylenesulfide (CFRP UD) was determined by an infrared camera. For the welding process a focal point with a homogenized intensity distribution was compared to different scanning structures, which were used to generate quasi-static temperature fields. All detected process temperatures and temperature distributions were affected by the fibre orientation of the CFRP material. For linear weld seams, the homogenized intensity distribution of the welding head generated a near-homogeneous temperature distribution over the width of the weld seam under consideration of the envelope of the maximum temperatures over the entire welding process. Compared to this, a scanning structure with scanning lines parallel to the axis feed generate an envelope with a temperature variation of about $\Delta T = 42°K$. Additionally, the welding process with a homogenized intensity distribution on a curved weld seam with a small radius was monitored, which generated an inhomogeneous temperature distribution. Based on these results the scanning structures were adapted to the curved weld seam geometry. So, the temperature distribution was optimized by $\Delta T_{\%} = 63\%$ by using scanning lines parallel to the axis feed. The near-homogeneous temperature distribution was generated with a scanning structure consisting of scanning lines perpendicular to the axis feed, which generated a temperature difference of $\Delta T = 3.7°K$ in the middle section of the weld seam. The corresponding envelope has an almost flat temperature profile over the width of the weld seam.

Based on these investigations, for later applications complex weld seams consisting of linear and curved sections can be welded with quasi-static temperature fields by adapting the scanning structure to the geometry of the weld seam. This welding strategy provides the possibility to generate weld seams with a constant quality.

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